



## Syntheses and Biological Evaluation of Novel 2 $\alpha$ -Substituted 1 $\alpha$ ,25-Dihydroxyvitamin D<sub>3</sub> Analogues

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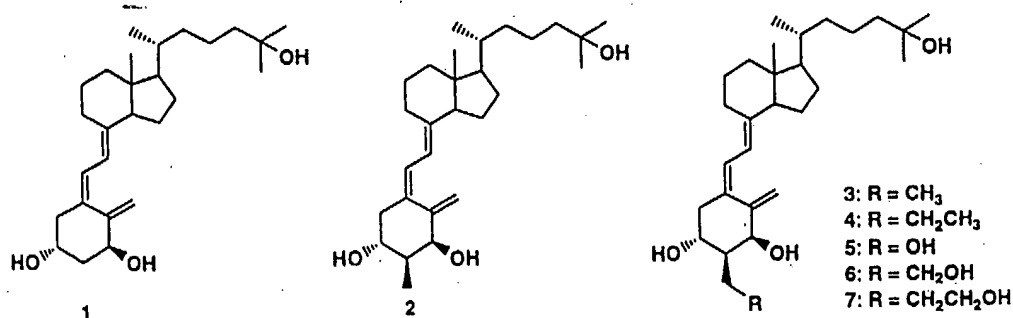
**Abstract**—Novel 2 $\alpha$ -substituted 1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> analogues were efficiently synthesized and their biological activities were evaluated. 2 $\alpha$ -Methyl-1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> (2), whose unique biological activities were previously reported, was modified to 2 $\alpha$ -alkyl (ethyl and propyl) and 2 $\alpha$ -hydroxyalkyl (hydroxymethyl, hydroxyethyl, and hydroxypropyl) analogues 3–7 by elongation of the alkyl chain and/or introduction of a terminal hydroxyl group. 2 $\alpha$ -Hydroxypropyl-1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> (7) exhibited an exceptionally potent calcium-regulating effect and a unique activity profile. © 2000 Elsevier Science Ltd. All rights reserved.

The growing interest in 1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> (1), the hormonally active form of vitamin D<sub>3</sub>, has prompted numerous efforts to synthesize vitamin D analogues as potential therapeutic agents.<sup>1</sup> A majority of them are modified in the side chain or in the A-ring.<sup>2</sup> A number of non-steroidal vitamin D mimics have been synthesized quite recently.<sup>3</sup>

In order to investigate the A-ring conformation–activity relationships, we synthesized all the possible A-ring diastereomers of 2-methyl-1,25-dihydroxyvitamin D<sub>3</sub> and found that the 2 $\alpha$ -methyl isomer (2) showed higher potency than 1 in terms of VDR binding affinity, elevation of rat serum Ca concentration, and induction of HL-60 cell differentiation.<sup>4</sup> Furthermore, the combination of this

2 $\alpha$ -methyl substitution with 20-epimerization, i.e., double modification, produced a much more potent analogue.<sup>5</sup> These results prompted us to design new analogues with further modification of the 2 $\alpha$ -methyl group. We anticipated that if the 2 $\alpha$ -methyl group were replaced by a longer 2 $\alpha$ -alkyl or the 2 $\alpha$ -hydroxyalkyl group, the resulting analogues would provide insight into the biological significance of the 2 $\alpha$ -methyl substitution. We report here the synthesis of several new analogues, 3–7, and their biological evaluation.

The analogues were synthesized according to the method developed by Trost and co-workers using palladium-catalyzed coupling of the A-ring enyne synthon with the CD-ring portion.<sup>6</sup> To introduce 2 $\alpha$ -substituents into 1,



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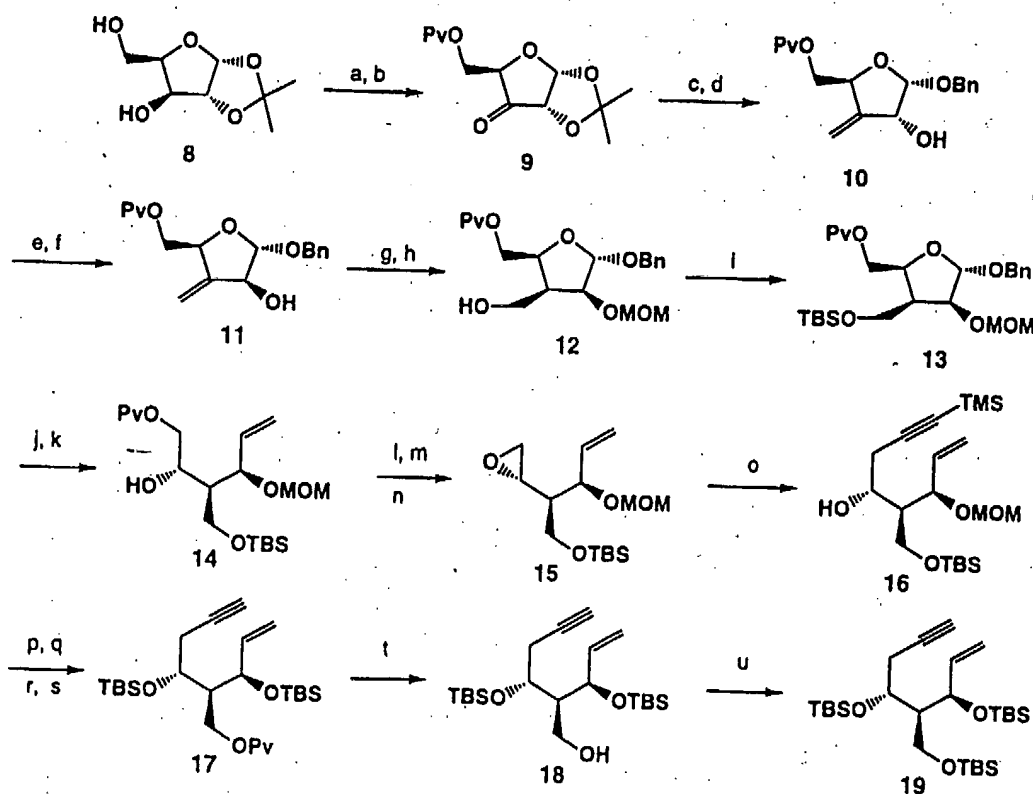
the synthesis of the A-ring portion was started with a D-xylose derivative (8), as shown in Scheme 1. Selective protection of the C-5 primary alcohol of 8 with a pivaloyl group, followed by oxidation with PCC gave the ketone 9 in 98% yield. Conversion of the ketone to an exomethylene group by means of the Wittig reaction, and subsequent treatment with 1 N HCl/BnOH afforded the alcohol 10 in 58% yield along with the  $\beta$ -isomer (32% yield). The C-2 hydroxyl group of 10 was inverted via the Mitsunobu reaction to give the secondary alcohol 11, corresponding to the 1 $\alpha$ -hydroxyl group of vitamin D analogues, in 84% yield. After protection of the alcohol moiety of 11 with a methoxymethyl (MOM) group, the exomethylene group was selectively converted to the 3 $\beta$ -hydroxymethyl compound 12 in high yield by hydroboration with 9-BBN. Protection of the primary hydroxyl group with a *tert*-butyldimethylsilyl (TBS) group afforded the TBS ether 13 in 99% yield. Thus, modification of the C-2 and C-3 hydroxyl groups of the D-xylose derivative, which correspond to the C-1 hydroxyl group and C-2 alkyl or hydroxyalkyl group of the vitamin D analogues, respectively, was accomplished.

The requisite A-ring synthons were obtained from the D-xylose derivative 13. Hydrogenolysis of the benzyl group of 13, followed by ring opening by means of the Wittig reaction afforded 14 in good yield. This was converted to the epoxide 15 by sequential treatment

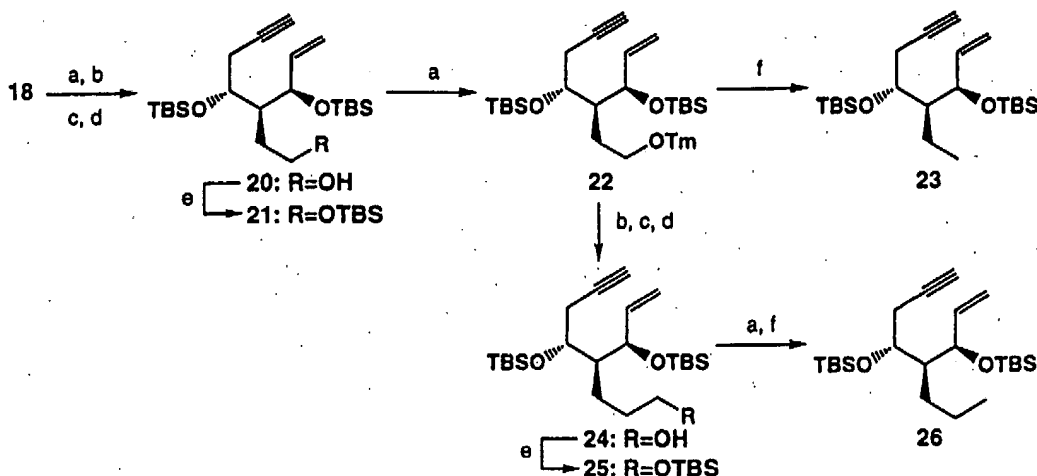
with DIBAL-H, 2,4,6-trimethylbenzenesulfonyl chloride (TmCl) and lithium hexamethyldisilazide (LiHMDS) in high yield. The acetylene unit was introduced by the reaction of 15 with (trimethylsilyl)acetylene/*n*-BuLi-BF<sub>3</sub>·OEt<sub>2</sub> in THF to give the alcohol 16 in 80% yield. Removal of both silyl protecting groups (TMS and TBS) by tetrabutylammonium fluoride (TBAF), and subsequent manipulation of the protecting groups by selective pivaloylation, removal of MOM group and silylation afforded the fully protected triol 17 in good yield. Finally, further protecting group manipulation through 18 gave the desired A-ring synthon 19 in high yield.

Elongation of the 2 $\alpha$ -substituent of the A-ring synthon was carried out in a conventional manner as shown in Scheme 2. Sequential sulfonylation, cyanide addition and reduction of the alcohol 18 furnished the single-carbon-elongated alcohol 20 in good overall yield, and this was protected to give the A-ring synthon 21. The alcohol 20 was further converted to the 2 $\alpha$ -ethyl derivative through the tosylate 22. In the same manner, the double-carbon-elongated synthons 25 and 26 were prepared from 22–24.

Finally, palladium-catalyzed coupling of the A-ring synthons 19, 21, 23, 25 and 26 with the CD-ring portion 27, followed by deprotection with camphorsulfonic acid (CSA) in MeOH gave the 2 $\alpha$ -alkyl and 2 $\alpha$ -hydroxyalkyl analogues 3–7<sup>7</sup> as shown in Scheme 3. Thus, we have



Scheme 1. (a)  $\text{PvCl}$ , Py, 86%; (b) PCC, MS 4A,  $\text{CH}_2\text{Cl}_2$ , 98%; (c)  $\text{Ph}_3\text{P}^+\text{CH}_3\text{Br}^-$ , KHMDS, THF, 85%; (d) 1 N HCl, BnOH, 1,4-dioxane/toluene, 58%; (e) *p*-nitrobenzoic acid,  $\text{Ph}_3\text{P}$ , DEAD, THF; (f) 10 mM NaOH,  $\text{H}_2\text{O}/\text{MeOH}$ , 84% (2 steps); (g) MOMCl, DPEA, TBAI,  $\text{CH}_2\text{Cl}_2$ , 88%; (h) 9-BBN, THF, then 3 M NaOH, 30%  $\text{H}_2\text{O}_2$ , 85%; (i) TBSCl, imidazole, DMF, 99%; (j)  $\text{H}_2$ , Pd(OH)<sub>2</sub>, EtOH; (k)  $\text{Ph}_3\text{P}^+\text{CH}_3\text{Br}^-$ , LiHMDS, THF, 80%; (l) DIBAL-H  $\text{CH}_2\text{Cl}_2$ , 84%; (m) TmCl, DMAP,  $\text{CH}_2\text{Cl}_2$ ; (n) LiHMDS, THF, 86% (2 steps); (o) TMS-C≡CH, *n*-BuLi, BF<sub>3</sub>·OEt<sub>2</sub>,  $\text{CH}_2\text{Cl}_2$ , 96%; (p) TBAF, THF, 99%; (q)  $\text{PvCl}$ , Py/ $\text{CH}_2\text{Cl}_2$ , 85%; (r) PPTS, *t*-BuOH, 74%; (s) TBSCl, imidazole, DMF, 88%.



Scheme 2. (a) TmCL, DMAP,  $\text{CH}_2\text{Cl}_2$ ; (b) NaCN, DMSO, 61–81% (2 steps); (c) DIBAL-H,  $\text{CH}_2\text{Cl}_2$ , 85–89%; (d)  $\text{NaBH}_4$ , MeOH, 82–98%; (e) TBSCl, imidazole, DMF, 78–83%; (f) LAH,  $\text{Et}_2\text{O}$ , 80% (2 steps).

synthesized five  $2\alpha$ -substituted  $1\alpha,25$ -dihydroxyvitamin  $\text{D}_3$  analogues.

The results of biological evaluation are summarized in Table 1, in comparison with those of  $1\alpha,25$ -dihydroxyvitamin  $\text{D}_3$  (1) and  $2\alpha$ -methyl- $1\alpha,25$ -dihydroxyvitamin  $\text{D}_3$  (2). First of all, we examined the receptor binding in an assay using bovine thymus VDR.<sup>8</sup> The  $2\alpha$ -alkyl analogues 3 and 4 showed much lower binding affinity than the  $2\alpha$ -methyl analogue 2; in other words, the shortest-chain analogue has the highest affinity among the  $2\alpha$ -alkyl analogues. In contrast, the  $2\alpha$ -hydroxypropyl analogue 7, bearing the most elongated chain, showed the highest binding affinity, 3-fold higher than that of 1, among the  $2\alpha$ -hydroxyalkyl analogues.<sup>9</sup> Therefore, the mode of binding of the  $2\alpha$ -hydroxyalkyl analogues may be different from that of the  $2\alpha$ -alkyl analogues. Steric hindrance of the  $2\alpha$ -alkyl group and hydrogen bonding ability of the  $2\alpha$ -hydroxyalkyl group are presumably involved in the difference of the mode of binding. Okano et al. previously reported the VDR binding affinity of  $2\beta$ -alkyl (methyl, ethyl, propyl, butyl, pentyl, and hexyl) and  $2\beta$ -hydroxyalkyl (hydroxypropyl, hydroxybutyl, hydroxypentyl, and hydroxyhexyl) analogues.<sup>10</sup> In contrast with those compounds, some of the  $2\alpha$ -substituted analogues showed significantly higher binding affinity than  $1\alpha,25$ -dihydroxyvitamin  $\text{D}_3$ .

Table 1. Relative potency of the synthesized analogues<sup>a</sup>

Compound	VDR <sup>b</sup> binding affinity	DBP <sup>c</sup> binding affinity	HL-60 cell <sup>d</sup> differentiation	Ca mobilization <sup>e</sup>
1 ( $1\alpha,25$ -(OH) $_2$ VD $_3$ )	100	100	100	100
2 ( $2\alpha$ -methyl)	400	44	444	658
3 ( $2\alpha$ -ethyl)	40	48	106	68
4 ( $2\alpha$ -propyl)	20	21	44	636
5 ( $2\alpha$ -hydroxymethyl)	20	95	10	124
6 ( $2\alpha$ -hydroxyethyl)	70	74	86	372
7 ( $2\alpha$ -hydroxypropyl)	300	362	240	50,866

<sup>a</sup>The potency of  $1\alpha,25$ -(OH) $_2$ VD $_3$  is normalized to 100 in each case.

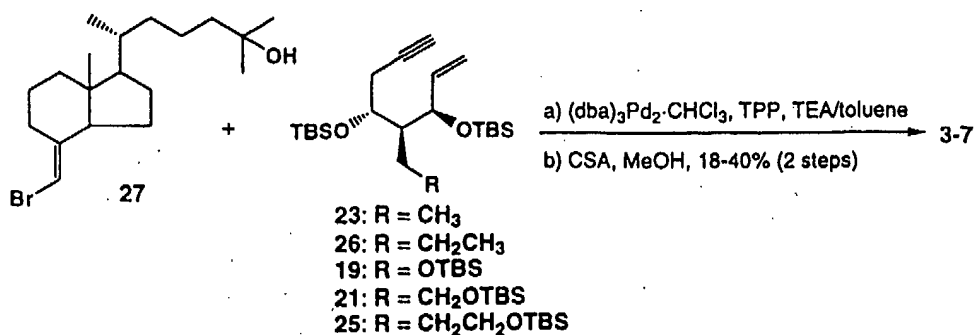
<sup>b</sup>Bovine thymus.

<sup>c</sup>Rat serum.

<sup>d</sup>Cell differentiation was assessed in terms of expression of antigen CD11b.

<sup>e</sup>Rat serum Ca level.

The affinity for vitamin D binding protein (DBP)<sup>11</sup> was tested using rat serum DBP. The binding affinity was decreased in the  $2\alpha$ -alkyl analogues including 2, whereas it was largely retained or even increased in the  $2\alpha$ -hydroxyalkyl analogues. In particular, the analogue 7 showed very high affinity for DBP, being similar in that respect to the  $\beta$ -isomer ( $2\beta$ -hydroxypropoxy- $1\alpha,25$ -dihydroxyvitamin  $\text{D}_3$ : ED-71).<sup>12</sup> This result implies that



Scheme 3.

there is no discrimination between the  $\alpha$ - and  $\beta$ -isomers of the 2-hydroxypropyl analogues in DBP binding.

The rank order of potency for inducing differentiation in HL-60 cells<sup>13</sup> was parallel to that of VDR binding; that is, as the chain length became longer, the potency decreased in 2 $\alpha$ -alkyl analogues, whereas it increased in the 2 $\alpha$ -hydroxyalkyl analogues. Only compounds 2 and 7 showed much higher activity than 1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> in this experiment.

Most of the new analogues exhibited higher calcium-mobilizing activity<sup>14</sup> than 1; in particular, the analogue 7 showed approximately 500 times higher potency, and this remarkably high activity is unique among vitamin D analogues reported to date. Therefore, this 2 $\alpha$ -hydroxypropyl analogue 7 may provide clues to achieving separation of the biological functions of vitamin D. In the case of the hydroxyalkyl series, the longer the chain, the higher the activity. This rank order of potency is parallel to that of VDR binding affinity, implying that the calcium-regulating effect of the 2 $\alpha$ -hydroxyalkyl analogues may involve interaction with VDR. In the alkyl series, in which VDR binding affinity decreased with increasing chain length, the 2 $\alpha$ -propyl analogue 4 showed anomalously high calcium-mobilizing activity, comparable to that of 2. This result is not easy to rationalize in terms of a VDR-dependent mechanism, and therefore, the analogue 4 may exert its calcium-regulating effect through a distinct mechanism from the other analogues.

Thus, the activity profiles of the synthesized analogues are high structure-sensitive, in that even a single-carbon chain difference greatly alters the profile. Consequently, these analogues should be useful for studies on the action mechanism of vitamin D, and also as lead compounds for developing therapeutic agents. Further studies, however, are needed to elucidate fully the activity profiles and modes of action of these analogues.

In this study, we have developed a synthetic route to A-ring enyne synthon, which can be useful for 2 $\alpha$ -substituted vitamin D analogues, starting from D-xylose, and utilized it for the synthesis of five novel 2 $\alpha$ -substituted vitamin D analogues 3–7 by palladium-catalyzed convergent method. In the light of the importance of 2-substituted vitamin D analogues, as exemplified by ED-71,<sup>10,12</sup> this novel procedure has a great advantage, because it should be applicable to a variety of 2 $\alpha$ -substituted vitamin D analogues. Biological evaluation of these analogues demonstrated that they have unique activity profiles, and in particular, the 2 $\alpha$ -hydroxypropyl analogue 7 exhibited exceptionally potent calcium-regulating activity. Further investigation along this line should provide insight into the biological significance of 2-substituted vitamin D analogues.

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#### References and Notes

- Ettinger, R. A.; DeLuca, H. F. *Adv. Drug Res.* 1996, 28, 269.
- Bouillon, R.; Okamura, W. H.; Norman, A. W. *Endocr. Rev.* 1995, 16, 200.
- Boehm, M. F.; Fitzgerald, P.; Zou, A.; Elgort, M. G.; Bischoff, E. D.; Mere, L.; Mais, D. E.; Bissonnette, R. P.; Heyman, R. A.; Nadzan, A. M.; Reichman, M.; Allegretto, E. A. *Chem. Biol.* 1999, 6, 265.
- Konno, K.; Maki, S.; Fujishima, T.; Liu, Z.-P.; Miura, D.; Chokki, M.; Takayama, H. *Bioorg. Med. Chem. Lett.* 1998, 8, 151.
- Fujishima, T.; Liu, Z.-P.; Miura, D.; Chokki, M.; Ishizuka, S.; Konno, K.; Takayama, H. *Bioorg. Med. Chem. Lett.* 1998, 8, 2145.
- Trost, B. M.; Dumas, J.; Villa, M. *J. Am. Chem. Soc.* 1992, 114, 9836.
- 3: <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>-D<sub>2</sub>O/TMS)  $\delta$  0.53 (3H, s), 0.94 (d, 3H,  $J$  = 6.6 Hz), 0.95 (3H, t,  $J$  = 7.4 Hz), 1.21 (6H, s), 2.24 (1H, dd,  $J$  = 8.0, 12.8 Hz), 2.66 (1H, dd,  $J$  = 4.4, 12.8 Hz), 2.83 (1H, m), 3.89 (1H, dt,  $J$  = 4.4, 8.0 Hz), 4.39 (1H, d,  $J$  = 2.2 Hz), 4.99 (1H, d,  $J$  = 2.2 Hz), 5.27 (1H, d,  $J$  = 1.5 Hz), 6.00 (1H, d,  $J$  = 11.4 Hz), 6.40 (1H, d,  $J$  = 11.4 Hz); HREIMS 444.3604 calcd for C<sub>29</sub>H<sub>48</sub>O<sub>3</sub> (M<sup>+</sup>) 444.3603. 4: <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>-D<sub>2</sub>O/TMS)  $\delta$  0.53 (3H, s), 0.94 (3H, d,  $J$  = 6.4 Hz), 1.01 (3H, t,  $J$  = 6.8 Hz), 1.21 (6H, s), 2.24 (1H, dd,  $J$  = 8.4, 13.2 Hz), 2.66 (1H, dd,  $J$  = 4.0, 13.2 Hz), 2.83 (1H, m), 3.88 (1H, dt,  $J$  = 4.4, 8.4 Hz), 4.36 (1H, d,  $J$  = 3.3 Hz), 4.99 (1H, d,  $J$  = 1.8 Hz), 5.26 (1H, d,  $J$  = 1.8 Hz), 6.00 (1H, d,  $J$  = 11.4 Hz), 6.40 (1H, d,  $J$  = 11.4 Hz); HREIMS 458.3755 calcd for C<sub>30</sub>H<sub>50</sub>O<sub>3</sub> (M<sup>+</sup>) 458.3760. 5: <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>-D<sub>2</sub>O/TMS)  $\delta$  0.53 (3H, s), 0.94 (3H, d,  $J$  = 6.8 Hz), 1.21 (6H, s), 2.31 (2H, dd,  $J$  = 9.9, 13.0 Hz), 2.67 (1H, dd,  $J$  = 4.6, 13.0 Hz), 2.84 (1H, m), 3.96 (1H, dd,  $J$  = 4.6, 11.2 Hz), 4.05 (1H, dd,  $J$  = 4.6, 11.2 Hz), 4.24 (1H, dt,  $J$  = 4.6, 9.9 Hz), 4.46 (1H, d,  $J$  = 2.9 Hz), 5.02 (1H, d,  $J$  = 1.8 Hz), 5.29 (1H, d,  $J$  = 1.8 Hz), 5.98 (1H, d,  $J$  = 11.0 Hz), 6.45 (1H, d,  $J$  = 11.0 Hz); HREIMS  $m/z$  428.3287 calcd for C<sub>28</sub>H<sub>44</sub>O<sub>3</sub> (M<sup>+</sup> - H<sub>2</sub>O) 428.3290. 6: <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>-D<sub>2</sub>O/TMS)  $\delta$  0.53 (3H, s), 0.94 (3H, d,  $J$  = 6.4 Hz), 1.21 (6H, s), 2.26 (1H, dd,  $J$  = 8.0, 13.0 Hz), 2.66 (1H, dd,  $J$  = 4.0, 13.0 Hz), 2.83 (1H, m), 3.79 (2H, m), 3.94 (1H, dt,  $J$  = 4.0, 8.0 Hz), 4.37 (1H, d,  $J$  = 2.2 Hz), 5.02 (1H, d,  $J$  = 1.8 Hz), 5.30 (1H, bs), 6.01 (1H, d,  $J$  = 11.2 Hz), 6.40 (1H, d,  $J$  = 11.2 Hz); HREIMS  $m/z$  460.3557 calcd for C<sub>29</sub>H<sub>48</sub>O<sub>4</sub> (M<sup>+</sup>) 460.3553. 7: <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>-D<sub>2</sub>O/TMS)  $\delta$  0.53 (3H, s), 0.93 (3H, d,  $J$  = 6.6 Hz), 1.21 (6H, s), 2.25 (1H, dd,  $J$  = 8.0, 13.2 Hz), 2.66 (1H, dd,  $J$  = 4.0, 13.2 Hz), 2.83 (1H, m), 3.71 (2H, t,  $J$  = 5.6 Hz), 3.90 (dt, 1H,  $J$  = 4.0, 8.0 Hz), 4.38 (d, 1H,  $J$  = 2.9 Hz), 5.00 (1H, d,  $J$  = 1.8 Hz), 5.28 (1H, bs), 6.00 (1H, d,  $J$  = 11.2 Hz), 6.40 (1H, d,  $J$  = 11.2 Hz); HREIMS 474.3709 calcd for C<sub>30</sub>H<sub>50</sub>O<sub>4</sub> (M<sup>+</sup>) 474.3709.
- Imae, Y.; Manaka, A.; Yoshida, N.; Ishimi, Y.; Shinki, T.; Abe, E.; Suda, T.; Konno, K.; Takayama, H.; Yamada, S. *Biochim. Biophys. Acta.* 1994, 1213, 302.
- Posner et al. previously reported that a 2 $\alpha$ -hydroxybutyl-1 $\alpha$ ,25-dihydroxyvitamin D<sub>3</sub> analogue had virtually no affinity for VDR. Posner, G. H.; Johnson, N. *J. Org. Chem.* 1994, 59, 7855.
- (a) Ono, Y.; Watanabe, H.; Shiraiishi, H.; Takeda, S.; Higuchi, Y.; Sato, K.; Tsugawa, N.; Okano, T.; Kobayashi, T.; Kubodera, N. *Chem. Pharm. Bull.* 1997, 45, 1626. (b) Tsugawa, N.; Nakagawa, K.; Kurobe, M.; Ono, Y.; Kubodera, N.; Ozono, K.; Okano, T. *Biol. Pharm. Bull.* 2000, 23, 66.
- Zhao, X. Y.; Eccleshall, T. R.; Krishnan, A. V.; Gross, C.; Feldman, D. *Mol. Endocrinol.* 1997, 11, 366.
- Okano, T.; Tsugawa, N.; Matsuda, S.; Takeuchi, A.; Kobayashi, T.; Takita, Y.; Nishii, Y. *Biochem. Biophys. Res. Commun.* 1989, 163, 1444.
- Brackman, D.; Lund-Johansen, F.; Aarskog, D. *J. Leukocyte Biol.* 1995, 58, 547.
- Ishizuka, S.; Norman, A. W. *J. Steroid Biochem.* 1986, 25, 505.